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Temperature Influence on Wall-to-Particle Suspension Heat Transfer in a Solar Tubular Receiver

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Abstract. Dense Particle Suspension (DPS) can be used as high temperature heat transfer fluid in solar receiver. Tests conducted with a one-tube experimental setup in real conditions of concentrated solar irradiation resulted in determining heat transfer coefficients for the DPS flowing upward in a vertical tube. They have been obtained for solid fluxes in the range 10-45 kg/m^2.s and outlet temperatures up to 1020 K. The influence of solid flux, aeration and temperature is outlined in this paper. Heat transfer coefficient variations are correlated as a function of the solid flux and the temperature for given aeration conditions.

INTRODUCTION

The efficiency of solar tower power plants is directly linked to the type of Heat Transfer Fluid (HTF) used in the receiver. According to Carnot's theorem, the hotter the HTF gets in the receiver, the higher the energy conversion system efficiency is. This is why the concept of using solid particles as heat transfer media is interesting, since some solids can withstand very high temperatures, contrary to currently used solar HTFs. Moreover, thermal storage, a key point for thermal solar power plant development, can be directly achieved by storing the heated particles, which is much simpler than when using a gas as HTF.

Another factor to take into account is the capacity of the HTF to exchange heat with a wall. Indeed, it was shown that the higher the solar concentration ratio, the higher the receiver efficiency [1]. For solid particle solar receivers, two options are opened, direct or indirect particle heating [2, 3]. In the case of indirect absorption of solar energy, which concerns most current solar receivers, the solar radiation is first absorbed by an opaque solid absorber before being transmitted to the HTF. As a consequence, the mechanical properties of the absorber wall imposes a temperature limit, while the intensity of heat exchange with the HTF sets the heat flux density that can be extracted. So the maximum concentration ratio admissible by the receiver is determined by the wall-to-fluid Heat Transfer Coefficient (HTC).

The process of Dense Particle Suspension (DPS) circulating in a vertical tube was tested with a one-tube experimental pilot plant at the 1 MW solar furnace of the French National Center for Scientific Research (Centre National de la Recherche Scientifique, CNRS), in the PROMES laboratory at Odeillo. This work was part of the CSP2 European project [4]. Two experimental campaigns were conducted between October 2012 and June 2014.

The first campaign proved that it is actually possible to use DPS as HTF in a solar receiver [3, 5]. The experimental measurements also allowed calculating the first values of the Heat Transfer Coefficient (HTC) of the DPS circulating upward in a vertical tube. Moreover, the HTC increase with the solid flow rate and decrease with the aeration were outlined.

The second campaign, after some modifications of the experimental setup including the addition of a particle pre-heating system, allowed working at higher temperature [6]. The DPS outlet temperature reached 1020 K,

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proving that this new HTF is a candidate for the third generation of high temperature solar tower power plants. At the same time, the existence of a particle reflux inside the absorber tube, with a downward flow close to the wall and an upward flow in the center, was underlined. It was confirmed by the work of the CSP2 European project partners [7]. This flow pattern led to a new method for calculating the HTC, whose values were actually higher than the ones previously determined. The HTC ranged from 420 W/m^2.K to 1100 W/m^2.K for solid fluxes of 10 kg/m^2.s and 45 kg/m^2.s respectively. The positive effect of the solid flux on the HTC was confirmed. By comparing the results obtained in the same flow conditions but for different DPS temperatures, a positive influence of temperature on the HTC was also evidenced.

In this paper, HTC experimental results are correlated as a function of the solid flux and the temperature, for two groups of data points, at high and low aeration respectively.

NOMENCLATURE

TABLE 1. Nomenclature

Latin Symbols		**Greek Symbols**	
A	internal surface area of the irradiated part of the receiver tube	ΔT_{lm}	logarithmic-mean temperature difference [K]
a, b, c, d	coefficients for the SiC specific heat capacity correlation	ρ	density [kg/m^3]
c_p	specific heat capacity [J/kg.K]	Φ	heat flux transferred to the DPS
e	slope for the HTC linear fit function of the solid flux [J/ K.kg]		
F	mass flow rate [kg/.s]		
f	y-intercept for the HTC linear fit function of the solid flux [W/m^2.K]		
G	mass flux [kg/m^2.s]		
h_{tube}	average heat transfer coefficient on the irradiated part of the tube [W/m^2.K]		
i, k	slopes for a and b linear fits functions of the temperature [J/ K^2.kg] and [W/m^2.K^2]		
j, l	y-intercepts for a and b linear fits functions of the temperature [J/ K.kg] and [W/m^2.K]		
T	temperature [K]		
Subscripts/Superscripts		**Acronyms**	
iDiFB	tube inlet in the dispenser fluidized bed	ColFB	Collector Fluidized Bed
o,center	outlet of the irradiated part of the tube, in the tube center	DiFB	Dispenser Fluidized Bed
p	refers to the particles	DPS	Dense Particle Suspension
SiC	refers to the silicon carbide	FB	Fluidized Bed
		HTC	Heat Transfer Coefficient
		HTF	Heat Transfer Fluid

ONE-TUBE EXPERIMENTAL SETUP

Experimental Setup Description and Functioning Principle

The one-tube experimental setup was already described in [3, 5], and the improvements made to increase the working temperature detailed in [6]. Therefore, only a short explanation is given here.

Particles are fed from a storage tank to a Fluidized Bed (FB) located at the bottom of the installation, called Dispenser FB (DiFB). The particles are fluidized by injecting air through a sintered metal plate at the bottom of the bed. The air flow rate is set to be in the bubbling regime. Particles can be pre-heated thanks to three 1.5 kW electrical resistances set inside the DiFB. The freeboard pressure is controlled with a regulation valve set on the air evacuation tube. A vertical stainless steel tube plunges into the DiFB, with its inlet located 0.06 m above the fluidization plate. The tube goes up to a FB at the top of the installation, called Collector FB (ColFB), which is at atmospheric pressure. The particles go up the tube in a state of DPS under the effect of the pressure difference between DiFB and ColFB, with a particle volume fraction ranging from 20 % to 40 %, depending on the flow conditions and temperature. A secondary air flow rate, called aeration, is injected in the tube 0.34 m above the DiFB fluidization plate. It allows controlling the DPS volume fraction and prevents any suspension subsiding. The tube passes through an insulated cylindrical cavity opened on the front to let the concentrated solar radiation reach it. The irradiated tube is heated and transfers the heat to the DPS circulating inside. The heated DPS then reaches the ColFB, flows down a conduct and exits the system. The DiFB has a square section of 0.40 m x 0.40 m and the ColFB is cylindrical with an inside diameter of 0.136 m. The absorber tube has an outside diameter of 0.0424 m, a wall thickness of 0.0032 m and is made of AISI 310S stainless steel. The irradiated part of the tube is 0.5 m high and goes from 1.1 m to 1.6 m above the DiFB fluidization plate. The cavity is cylindrical with a 0.1 m diameter.

The air injections are controlled by mass flow-meters. A rotary valve set between the storage tank and the DiFB sets the solid flow rate, which is then verified by an electronic scale at the system outlet. The pressure is measured in the DiFB freeboard, in the bed at the tube inlet height, and in the tube 0.54 m and 1.96 m above the DiFB fluidization plate. K thermocouples measure the DPS temperature in the beds, at the tube inlet, and inside the tube at the inlet and outlet of the irradiated part at two positions: 5 mm from the wall and at the center. In a fluidized bed, it was demonstrated [8] that the gas and solid temperatures are equal.

The external tube wall temperature is measured with welded K thermocouples at 8 positions in the cavity: at the inlet and outlet on the east and west sides, in the middle of the cavity on the front, back, east and west sides of the tube (the concentrated radiation comes from the south, therefore the south side of the tube is called front).

Pressure measurements are used to determine the void fraction of the DPS, neglecting the pressure loss due to friction and therefore admitting that the pressure drop is due exclusively to the particles' weight. Temperature measurements are used to calculate the power absorbed by the DPS and the temperature difference between the DPS and tube wall in the irradiated part of the tube, which allows calculating the HTC.

Silicon Carbide Particles Properties

The particles used in the experimental are Silicon Carbide (SiC) particles with a 64 µm average Sauter diameter. The SiC density was measured and is equal to 3210 kg/m^3. The specific heat capacity $c_{p,SiC}$ is expressed in the form of a polynomial that was established with the data from the NIST database [9], as a function of the particle temperature T_p in K:

$$c_{p,SiC} = aT_p^{\ 3} + bT_p^{\ 2} + cT_p + d \tag{1}$$

in [J/kg.K], with a = 2.25 10^{-7} J/kg.K^4, b = -9.88 10^{-4} J/kg.K^3, c = 1.62 J/kg.K^2, d = 320 J/kg.K.

HEAT TRANSFER COEFFICIENT

The HTC calculation was detailed in [6], so a shortened explanation is given hereafter. All the values used for the HTC calculation are averaged over stable periods ranging from 6 min to 30 min. The method applied used an enthalpy balance to determine the heat flux Φ transferred to the DPS. Due to the recirculation flux, the inlet temperature used is not the one at the inlet of the irradiated part of the tube because it does not account for the heated particles going downward close to the wall, which mix with the colder upward flow. The temperature at the tube inlet in the DiFB, $T_{p,i,DiFB}$, is used instead. The outlet temperature used is the temperature measured at the outlet of the irradiated part in the center of the tube, $T_{p,o,center}$. The solid flow rate F_p is known thanks to the measurement of the solid mass exiting the system. Finally, the formula used for calculating the heat flux received by the particle suspension is:

$$\Phi = F_p c_{p,SiC} \left(T_{p,o,center} - T_{p,iDiFB} \right) \tag{2}$$

with $c_{p,SiC}$ the particle specific heat capacity calculated at the average of the inlet and outlet temperatures.

$T_{p,o,center}$ is affected by the downward particle flow cooled above the cavity due to the tube not being insulated, but no better data was available. Therefore the heat flux calculated is inferior to the actual heat flux transferred to the DPS. It will result in underestimated values of the HTC. The extent to which this method underestimates the heat flux and the HTC depends on the solid flux because simulations and Positron Emission Particle Tracking (PEPT) measurements have shown that the higher the solid flux, the lower the ratio of downward flux over ascending flux. However, the exact ratio for each case is unknown (PEPT measurements were done only at ambient temperature, the recirculation is overestimated by simulations). By considering that the recirculation ratio is 50 % and that the downward flux temperature is equal to the temperature measured 5 mm from the wall at the cavity outlet, the actual heat fluxes and HTCs are estimated to be about 10 % higher than those calculated with this method.

To obtain the global HTC between the irradiated part of the tube and the DPS, noted h_{tube}, the heat flux Φ calculated is divided by the internal surface area of the irradiated part of the receiver tube, A, and by the logarithmic-mean temperature difference between the DPS and the tube wall, ΔT_{lm}, which was calculated in a way that takes into account the temperatures on all sides of the tube (see [6]):

$$h_{tube} = \frac{\Phi}{A\Delta T_{lm}} \tag{3}$$

This method implies approximations that impact the results. As mentioned, the recirculation flux leads to an underestimation of the outlet temperature. The concentrated solar flux is higher on the tube front than on the back, but for lack of a better option it is considered uniform (but real temperature distribution is taken into account in the h_{tube} calculation). Moreover, hot spots may exist on the front, because the tube is not set in the solar furnace focus plane where the homogeneity is achieved. Finally, the limited number of thermocouples measuring the DPS and wall temperatures may induce errors on the ΔT_{lm}, but installing more thermocouples was not possible. The sheathed thermocouples measuring the DPS would have hindered the DPS flow and their passages through the tube wall would have caused problems, both at the level of the tube integrity and incoming flux perturbation since they would have been exposed to the concentrated solar flux. Finally, welded thermocouples being very fragile, they broke several times rendering several experimental runs unusable. More welded thermocouples would have meant even more breakages and unusable data.

TEMPERATURE INFLUENCE ON THE DPS HEAT TRANSFER COEFFICIENT

Previous Analysis

Observing the influence temperature on the HTC based only on the experimental data proved to be complicated. Indeed, four operation parameters were varied during the experimental campaign: the solid flow rate, the aeration, the concentrated solar flux density and the temperature in the DiFB. Each of them affects directly or indirectly the DPS temperature in the irradiated part of the tube. As a consequence, it is difficult to obtain data points that have the same flow conditions (same solid flow rate and same particle volume fraction) but different DPS temperatures in the irradiated part of the tube. In a previous publication [6], we selected 5 points that were obtained for the same aeration, and close values of solid flow rate and solar flux density, but different DPS temperatures. The suspension temperature considered is $T_{p,cav}$ the average of the four temperatures measured in the irradiated part of the tube. This outlined a positive effect of the temperature on the HTC since it increases from 530 W/m^2.K at 590 K to 670 W/m^2.K at 850 K. This can be explained by a combination of two factors put in evidence in earlier works [10, 11]. It is not showed here but evidently the wall temperature increases with the particle temperature and the radiation flux increases greatly with the increase of the wall temperature. Also, the increase of air thermal conductivity enhances the heat transfer by conduction at the wall.

Heat Transfer Coefficient Correlation

Analysis Method

Since the temperature impacts the DPS heat transfer, we tried to establish a correlation to predict the HTC that would include this effect. In order two distinguish the temperature influence separately from the other parameters, the analysis of the results was done for two data groups that have different values of aeration: a low aeration, 0.021 kg/m^2.s and a high aeration, 0.042 kg/m^2.s. Each data group was then separated into two subgroups according to $T_{p,cav}$ (the average of the four temperatures measured in the irradiated part of the tube): a high temperature subgroup and a low-temperature subgroup. The characteristics of each group and subgroup are detailed in Table 2.

TABLE 2. Aeration groups and temperature subgroups characteristics

Low aeration = 0.021 kg/m^2.s		High aeration = 0.042 kg/m^2.s	
Low Temperature 437-519 K Average 467 K	High temperature 606-757 K Average 690K	Low Temperature 442-511 K Average 581 K	High temperature 652-838 K Average 735 K

For each subgroup, the HTC was plotted as a function of the solid flux G_p and a linear fit of the results was determined. For further analysis, the slope is called e and the y-intercept f. Figures 1 and 2 show the experimental HTC as a function of G_p, with linear fits, for the low aeration and high aeration groups respectively.

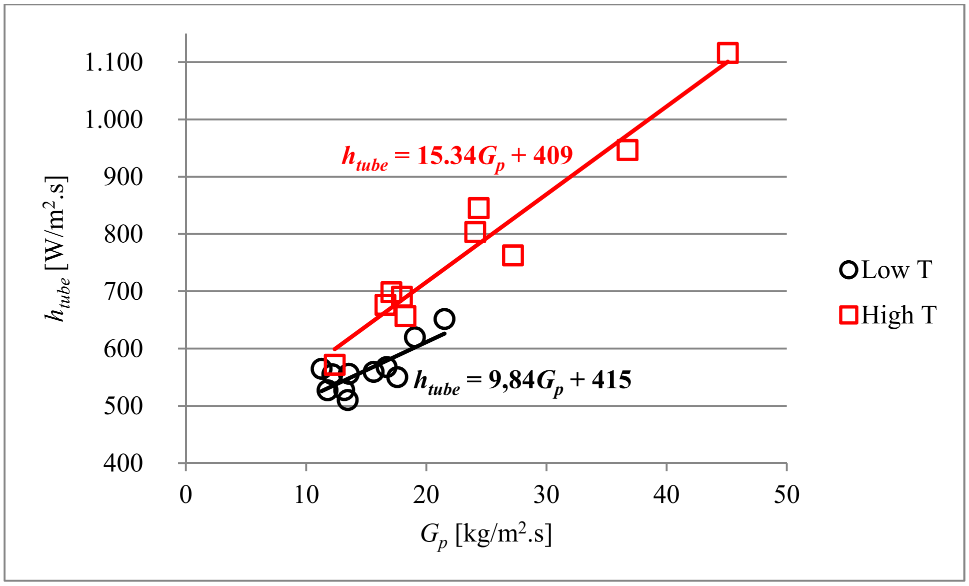

FIGURE 1. HTC versus solid flux with linear fits for the low aeration group

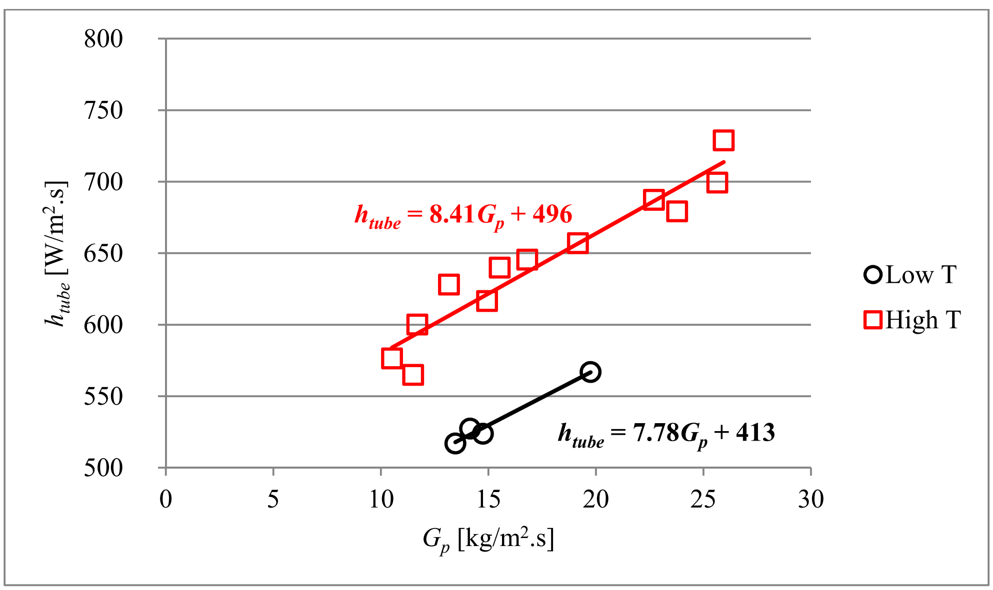

FIGURE 2. HTC versus solid flux with linear fits for the high aeration group

Table 3 lists the values of *a* and *b* obtained by the linear fits functions of the solid flux.

TABLE 3. Slopes and y-intercepts for the linear fits functions of the solid flux

Low aeration = 0.021 kg/m^2.s		**High aeration = 0.042 kg/m^2.s**	
Low Temperature	High temperature	Low Temperature	High temperature
e = 9.84 J/ K.kg	e = 15.34 J/ K.kg	e = 7.78 J/ K.kg	e = 8.41 J/ K.kg
f = 415 W/m^2.K	f = 409 W/m^2.K	f = 413 W/m^2.K	f = 496 W/m^2.K

Then for each group, a linear equation of the subgroups' slope as a function of the subgroups' average temperature was established. The same analysis was done for the y-intercept. The slope and y-intercept of the *e* and *f* linear fits are called *i*, *j* and *k*, *l* respectively. Their values for both aerations are displayed in Table 4. Note that the y-intercept values for both subgroups of the low aeration are almost the same. This is why, to simplify the final HTC correlation for this group, *k* was neglected and *l* was taken equal to the average *f* value.

TABLE 4. Slopes and y-intercepts for the second linear fits

Low aeration = 0.021 kg/m^2.s		**High aeration = 0.042 kg/m^2.s**	
e linear fit	*f* linear fit	*e* linear fit	*f* linear fit
i = 0.0247 J/ K^2.kg	$k \approx 0$ W/m^2.K^2	i = 0.0024 J/ K^2.kg	k = 0.34 W/m^2.K^2
j = -1.68 J/ K.kg	$l \approx 412$ W/m^2.K	j = 7.27 J/ K.kg	l = 339 W/m^2.K

Finally, a HTC correlation, function of the solid flux and the temperature, was obtained for each aeration group as:

$$h_{tube} = \left(iT_{p,cav} + j\right)G_p + \left(kT_{p,cav} + l\right) \qquad (4)$$

Correlations Comparison with Experimental Results

Figures 3 and 4 plot the HTC calculated with the correlation as a function of the experimental HTC for the low aeration and high aeration groups respectively. The average errors are 4.7 % and 2.8 %, and the maximum errors are 9 % and 10 % respectively. The maximum errors are observed for the extreme values of temperature. This is mainly due to the air density variation with the temperature that modifies the ratio of air velocity over minimum fluidization velocity, which creates a difference at the level of the suspension void fraction compared to the average of the data group.

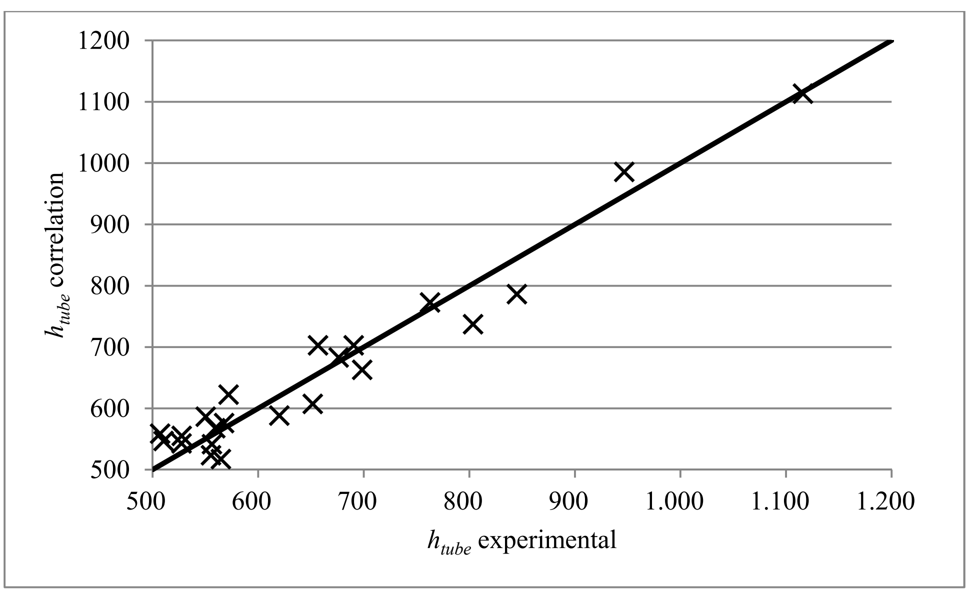

FIGURE 3. HTC calculated with the correlation as a function of the experimental HTC for the low aeration group

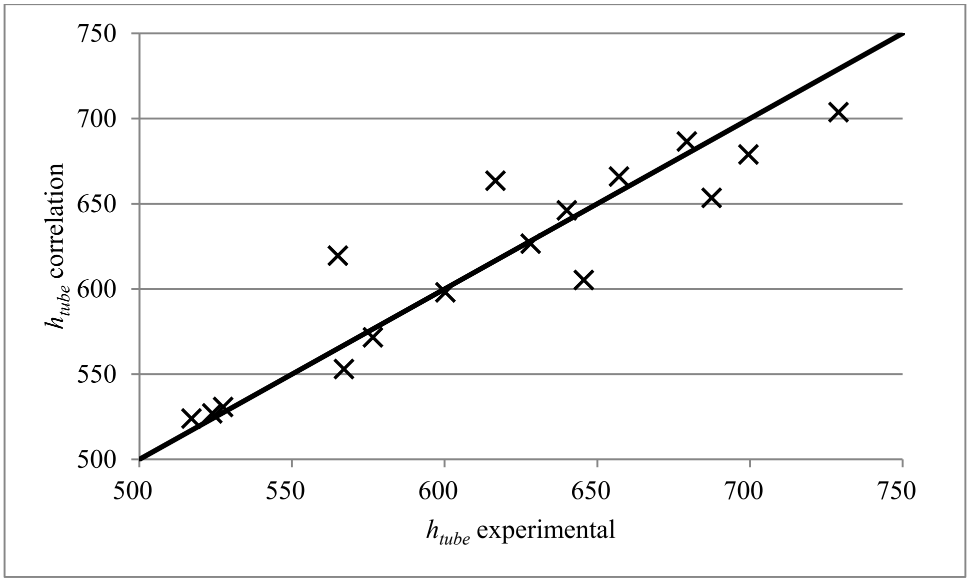

FIGURE 4. HTC calculated with the correlation as a function of the experimental HTC for the high aeration group

The results of these correlations are much better than the results of the correlation previously established in [6] based only on the solid flux. It can be concluded that the influence of temperature and aeration must be taken into account in addition to the solid flux when establishing a correlation for the HTC of DPS flow in a vertical tube.

CONCLUSION

The HTC experimental values for the DPS flow in a vertical tube resulting from two experimental campaigns were fitted with two correlations functions of the solid flux and temperature, each correlation being adapted to a specific aeration. The difference between experimental and calculated values is lower than 10 %. The next step of the study will be to establish a correlation applicable to the whole range of parameters tested. To achieve this goal, the temperature and aeration cannot be included as such in the correlations. Their influences should be taken into account through their impact on the phases' thermal properties (density, conductivity, heat capacity, viscosity) and on the DPS characteristics, the void fraction in particular.

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REFERENCES

1. C. K. Ho, B. D. Iverson. Review of high-temperature central receiver designs for concentrating solar power. Renewable and Sustainable Energy Reviews 29, 835-846 (2014).
2. J. Christian, C. Ho. Design and evaluation of an on-sun prototype falling-particle cavity receiver. Proceedings of ASME 8th Int. Conf. on Energy Sustainability & 12th Fuel cell Science, Engineering and Technology Conference. (June 30 – July 2, Boston, MA, USA, 2014), paper ES2014-6446.
3. G. Flamant, D. Gauthier, H. Benoit, J.-L. Sans, R. Garcia, B. Boissière, R. Ansart, M. Hemati. Dense suspension of solid particles as a new heat transfer fluid for concentrated solar thermal applications: On-sun proof of concept. Chemical Engineering Science 102, 567-576 (2013).
4. www.csp2-project.eu/

5. G. Flamant, D. Gauthier, H. Benoit, J.-L. Sans, B. Boissière, R. Ansart, M. Hemati. A New Heat Transfer Fluid for Concentrating Solar Systems: Particle Flow in Tubes. Energy Procedia 49, 617–626 (2014).
6. H. Benoit, I. Pérez López, D. Gauthier, J.-L. Sans, G. Flamant. On-sun demonstration of a 750 °C heat transfer fluid for concentrating solar systems: Dense particle suspension in tube. Solar Energy 118, 622–633 (2015).
7. P. Garcia-Triñanes, J. P. K. Seville, B. Boissiere, R. Ansart, T. W. Leadbeater, D. J. Parker. Hydrodynamics and particle motion in upward flowing dense particle suspensions: application in solar receivers. Chemical Engineering Science (submitted for publication).
8. J. Baeyens, W. R. A. Goossens. Some aspects of heat transfer between a vertical wall and a gas fluidized bed. Powder Technol. 8, 91–96 (1973).
9. R. G. Munro. Material properties of a sintered alpha-SiC. J. Phys. Chem. Ref. Data 26, 1195–1203 (1997).
10. G. Flamant, T. Ménigault. Combined wall-to-fluidized bed heat transfer. Bubbles and emulsion contributions at high temperature. Int. J. Heat Mass Transf. 30 (9), 1803–1812 (1987).
11. F. Pitié, C. Y. Zhao, J. Baeyens, J. Degrève, H. L. Zhang. Circulating fluidized bed heat recovery/storage and its potential to use coated phase-change-material (PCM) particles. Appl. Energy 109, 505-513 (2013).